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A Mode-Averaging Diversity Combiner

by
O. G. Villard, Jr.

December 1963

Technical Report No. 88

Prepared under
Office of Naval Research Contract
Nonr-225(64), NR 088 019, and
Advanced Research Projects Agency ARPA Order 196-63

RADIOSCIENCE LABORATORY
STANFORD ELECTRONICS LABORATORIES
STANFORD UNIVERSITY • STANFORD, CALIFORNIA

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A MODE-AVERAGING DIVERSITY COMBINER

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Radioscience Laboratory
Stanford Electronics Laboratories
Stanford University   Stanford, California

ABSTRACT

A diversity-combining technique is described which reduces frequency distortion caused by multipath propagation in high-frequency, single- or double-sideband, voice, radio transmission. By repetitively sweeping a null through the vertical polar pattern of the receiving antenna, the relative amplitude of signal components arriving by the various propagation modes is varied at a rate which is high compared with the highest audio modulating frequency. A running average of the time-varying resultant of the various mode voltages is diode rectified to extract the audio intelligence. Mode-interference-caused transmission nulls at particular frequencies in the radio spectrum are filled in by this averaging process. The technique requires no more equipment than conventional combining and would appear to offer superior performance.

CONTENTS

ILLUSTRATIONS

I. INTRODUCTION

The following is concerned with reducing the frequency distortion encountered in voice or broadband data transmission over high-frequency radio circuits subject to selective fading. The term "frequency distortion" used here has the same meaning as in audio-amplifier practice and has reference to the steady-state amplitude-of-transmission-vs-modulation-frequency characteristic of the radio circuit. As a result of selective fading, this characteristic is not flat; mode interference results in the existence of one or more nulls lying within the bandwidth of a voice channel. As the ionosphere changes, the position of these nulls in the spectrum drifts. When the position of a transmission null coincides with that of the carrier of an amplitude-modulated transmission, severe amplitude distortion due to overmodulation occurs if the receiver detector is a simple diode. Even when the carrier is strong, and such overmodulation does not occur, the presence of drifting transmission nulls at other frequencies within the passband causes changes in audio quality which are unnatural and which detract from intelligibility. The audible effect of these nulls can be simulated in the case of clean program material by slowly tuning a comparatively broad "notch filter" through the audio-frequency range.

Simple diversity combiners [Ref. 1] intended for radiotelephone use eliminate the carrier dropouts but do not improve the frequency distortion. The following note will describe an alternative approach to diversity combining in which a special kind of average is automatically taken of the contributions of the several modes which may be present to transmission at each audio frequency.

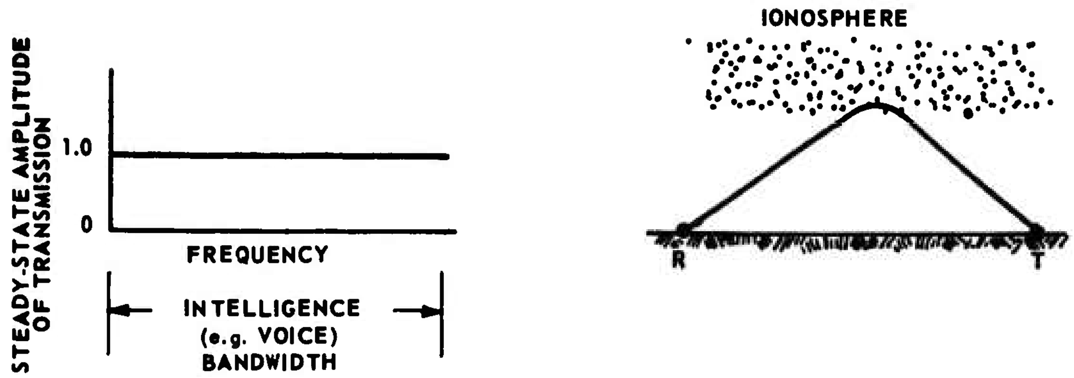
II. STATEMENT OF THE PROBLEM

Figure 1 shows the way in which frequency distortion in hf transmission arises. In part (a) it is assumed that only one ionospheric path exists between a given transmitter and receiver, a circumstance encountered comparatively seldom in practice. In this situation there can be no multipath, and the amplitude of transmission over the intelligence bandwidth will be independent of the radio frequency.

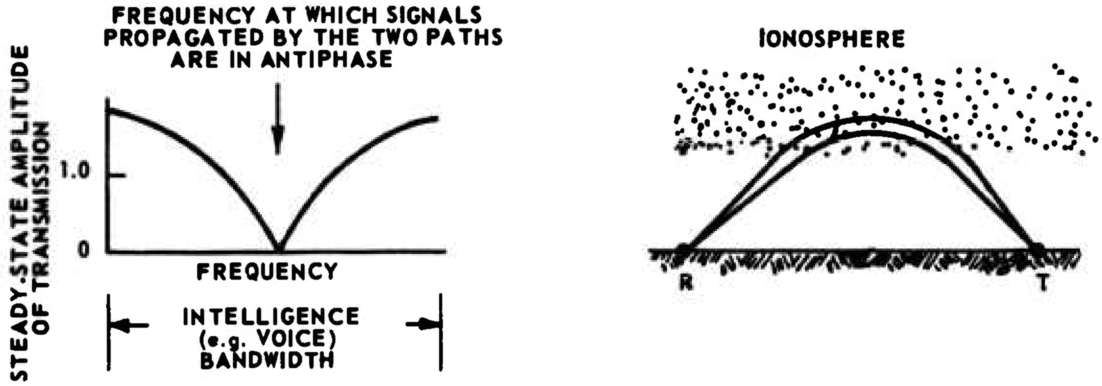
In Fig. 1(b), two transmission paths are shown, one an upper ray and the other a lower ray. Except for certain special situations, two such rays will always be present in one-hop transmission. In the state of affairs illustrated, it is assumed that the paths of the two rays do not diverge appreciably. Therefore, the transmission time delay will be nearly the same for both paths, and the amplitude of transmission for both will be nearly the same. At some radio frequency, marked by the arrow in Fig. 1(b), the phase of continuous-wave energy transmitted over one path will be opposite to that transmitted over the other, and cancellation of the resultant signal will result. At frequencies to either side of this "null frequency", the two individual-path contributions will no longer be in precise phase opposition, and partial transmission will take place.

If the radio frequency departs sufficiently from the null frequency, a point in the spectrum will usually be found at which cancellation once again takes place. The frequency separation between nulls is related to the difference in transmission time delay of the two paths [Ref. 2]. If the delay-time difference is small, the spacing of the nulls in the frequency spectrum is large.

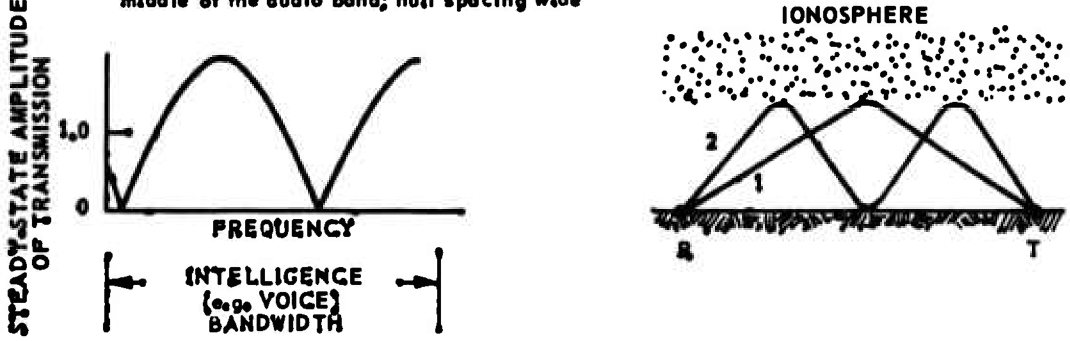
In part (c) of the figure, an important practical case is shown, where interference occurs between the one-hop and the two-hop modes. In practice, the spread in propagation delay times encountered in ionospheric transmission will normally not exceed 2 msec. It follows from this that the minimum spacing between transmission nulls in the frequency spectrum is in the order of 500 cps. The position of these nulls in the spectrum is subject to continuous change, owing to motion of the ionospheric layers, which alters the phase relationships between the signal contributions delivered by the various modes.



(a) One mode present; 'flat' (i.e. non-selective) fading



(b) Two modes (upper and lower ray) present; selective fading; null momentarily close to the middle of the audio band; null spacing wide



(c) Two modes (one hop and two hop) present; selective fading; two nulls within audio band; null spacing narrow

FIG. 1. FREQUENCY DISTORTION DUE TO MULTIPATH PROPAGATION.

It should be noted that the transmission-vs-frequency curves of Fig. 1 apply to the case of steady-state signals. By "steady state" is implied that signal components at--or very close to--a given radio frequency endure for a time interval long compared with the relative mode delay times. In the case of speech transmission, the steady-state picture is valid for most of the high-energy voice components, which have relatively long durations. However, some speech sounds, such as fricatives and sibilants, are highly transient. When a 2-msec relative time delay is present, a 1-msec transmitted impulse will appear to be doubled in duration at the receiver. In this situation, the steady-state viewpoint is meaningless, and the averaging procedure proposed in this note offers no advantage. However, much of the time, the inter-mode relative time-delay differences of significance will fall in the 200- to 500-μsec range. This is especially true of the shorter (i.e., several thousand kilometer) transmission paths. In this situation, mode averaging to reduce frequency distortion should offer real advantage in transmission of both speech and music.

III. PROPOSED SOLUTION

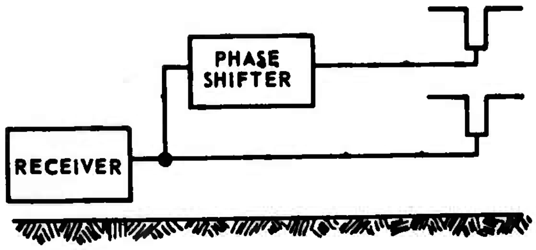
Consider the two-mode situation of Fig. 1(c). If, at the radio frequency at which a null occurs, some means can be found to upset the equality of transmission via the two modes, or to render the relative phase of the two voltages thus delivered to the receiving antenna other than opposite, the null could be removed, or at least shifted to another radio frequency. The problem is to find a way to do this continuously and automatically, so that no attention on the part of an operator is required.

To alter the relative amplitude (and, as an incidental, the relative phase) of the two downcoming rays of Fig. 1(c), it is possible to use variable antenna directivity as shown in Fig. 2(b). Since high-frequency propagation to a first approximation lies in the great-circle plane passing through transmitter and receiver, a steerable null in the vertical polar pattern of the receiving antenna is needed to alter relative mode amplitudes. The null can be adjusted so as to reject a particular mode, or received-signal component.

Such a null could be provided by means of an interferometer arrangement similar to that shown in Fig. 2(a). Antennas spaced vertically one above the other are shown, but two antennas of the same height spaced along the great-circle direction to the distant transmitter could also be used. The objective in either case is to generate a polar pattern which approximates the ideal form shown in Fig. 2(b). By varying the phase of the phase shifter illustrated in Fig. 2(a), it is assumed that a null will be caused to move through the vertical polar pattern of the interferometer. The three parts of Fig. 2(b) represent patterns obtained with three different settings of the phase shifter of Fig. 2(a).

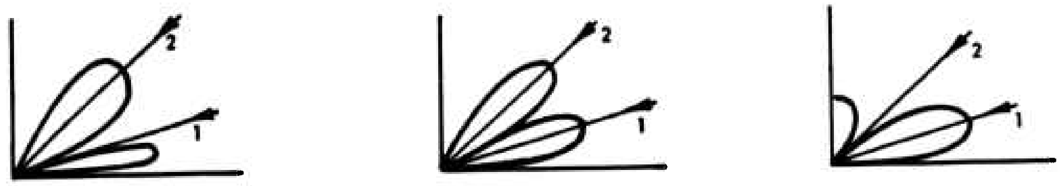
Part (c) of Fig. 2 shows the effect on the relative phase and amplitude of the two incoming mode voltages, of setting the pattern null to these three positions. First one mode is discriminated against, and then the other.

The resultant voltage delivered to the receiver for each of the three antenna patterns is shown in the phasor diagrams of parts (d), (e) and (f) of Fig. 2. The variation of this resultant voltage with the position of



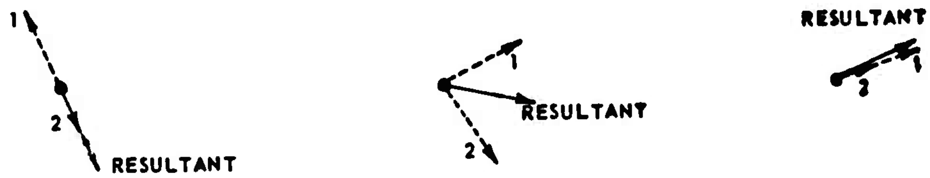
(a) Interferometer arrangement

(b) Idealized polar patterns corresponding to three different settings of the phase shifter of (a)

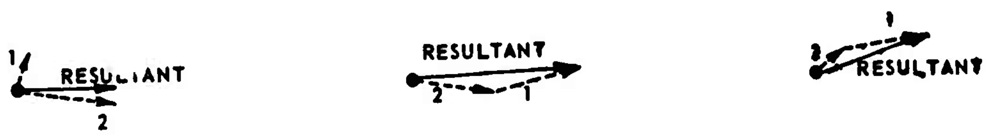


(c) Propagation paths of Fig. 1(c) superimposed on patterns of (b)

(d) Phasor diagrams, showing interferometer output for the three phase-shifter settings of part (c), assuming voltages from paths 1 and 2 initially in phase



(e) Same as (d), assuming 1 and 2 initially in quadrature phase



(f) Same as (d), assuming 1 and 2 initially nearly out of phase

FIG. 2. USE OF ANTENNA DIRECTIVITY TO BREAK UP FREQUENCY RESPONSE NULLS.

c

the pattern null depends on the relative phases of the two downcoming signal components.* Part (d) assumes that the mode voltages are in phase, part (e) in phase quadrature and part (f) in phase opposition.

Since the variation of the polar pattern (a sweeping of the pattern null, shown in Fig. 2(b), is assumed to be accomplished solely by varying the setting of the phase shifter, the pattern change will repeat one or more times each time the phase shift is changed by 360 deg. To form a kind of running "average" of the contributions of each mode, it is possible to repeat the pattern-null sweep at a rate which is high compared with the highest signal-modulating frequency. This could be done by motor driving the phase shifter at a sufficiently high rate. Such a continuous phase shift amounts to a frequency shift. In the arrangement of Fig. 2(a) an appreciable frequency shift would not be practical, because the receiver acceptance bandwidth would then have to be broadened in order to accept both the original signal frequency, and the shifted frequency coming from the output of the phase shifter. Such a bandwidth increase would admit interfering signals.

However, two separate narrow-band receivers could be used, each connected to an antenna element, as in Fig. 3. The phase (and frequency) shifting can then be done at the output of their respective i-f amplifier chains, without any problem due to increased bandwidth or interference. In practice, instead of a motor-driven phase shifter, simple frequency translation can be used. Thus, if the receivers were initially identical, the i-f output of one could be heterodyned to a frequency separated from that of the other by some convenient value, such as 45 kc. Alternatively, the receivers might be initially designed to have the same bandwidth but different center i-f frequencies. The exact frequency difference is unimportant, so long as it is well above the highest audio modulating frequency.

If the i-f voltages of the two receivers are then added, the situation at the input terminals of the diode detector is the same as if the phase shifter of Fig. 2(a) had been driven continuously at a rate sufficient to produce a 45-kc frequency shift and the i-f passband of the single receiver had been broadened accordingly.

Following the diode detector of Fig. 3 is a low-pass filter whose

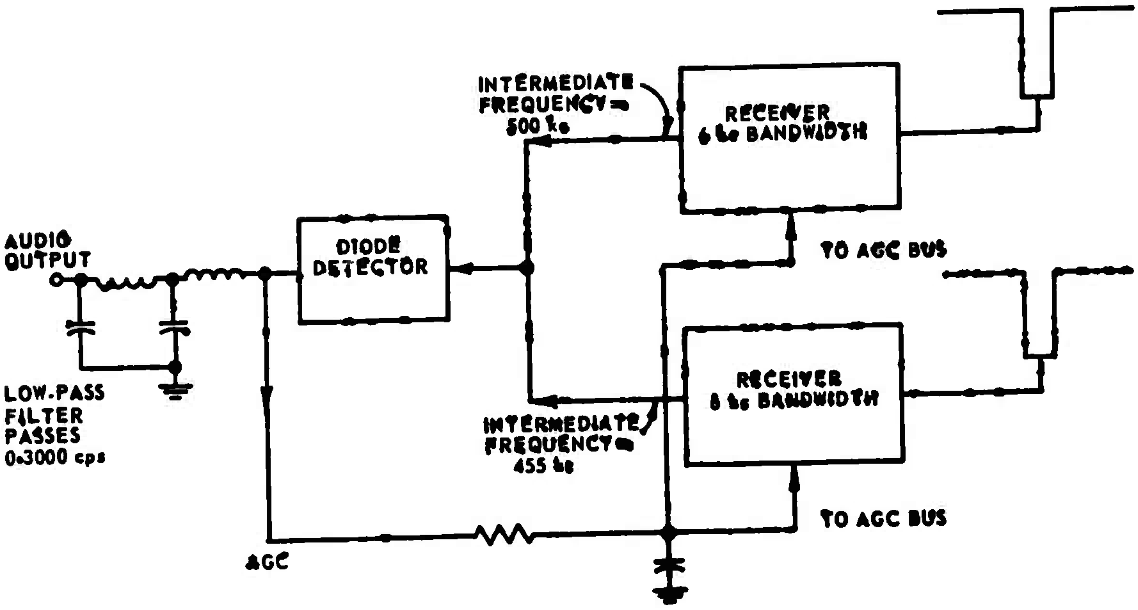


FIG. 3. MEANS FOR ACHIEVING EFFECT OF FIG. 2 AUTOMATICALLY, SUITABLE AS SHOWN, FOR DSB AM RECEPTION.

purpose is to reject any 45-kc beat frequency and to pass the desired modulation-frequency band. In order to produce interferometer action, the gains of the two receivers should at all times be equal. Thus an AGC voltage common to both receivers must be derived from the single diode load.

The operation of the arrangement of Fig. 3 can be visualized by reference to the wave forms of Fig. 4. For simplicity, let it be assumed initially that only one mode is present, as in Fig. 1(a). Each antenna then receives a steady voltage corresponding to that mode. Since the antennas have equal response and the receiver gains are equal, the two intermediate-frequency voltages will be equal in amplitude and will beat together at a 45-kc rate, as in Fig. 4(a). If the incoming signal is amplitude modulated at an audio rate, the intensity of both received signal components will vary in synchronism, and the envelope of the 45-kc beats will vary with time, as in Fig. 4(b). The demodulated envelope of this wave form, appearing at the output terminals of the low-pass filter, is shown in Fig. 4(c); this should be a replica of the transmitter modulating voltage.

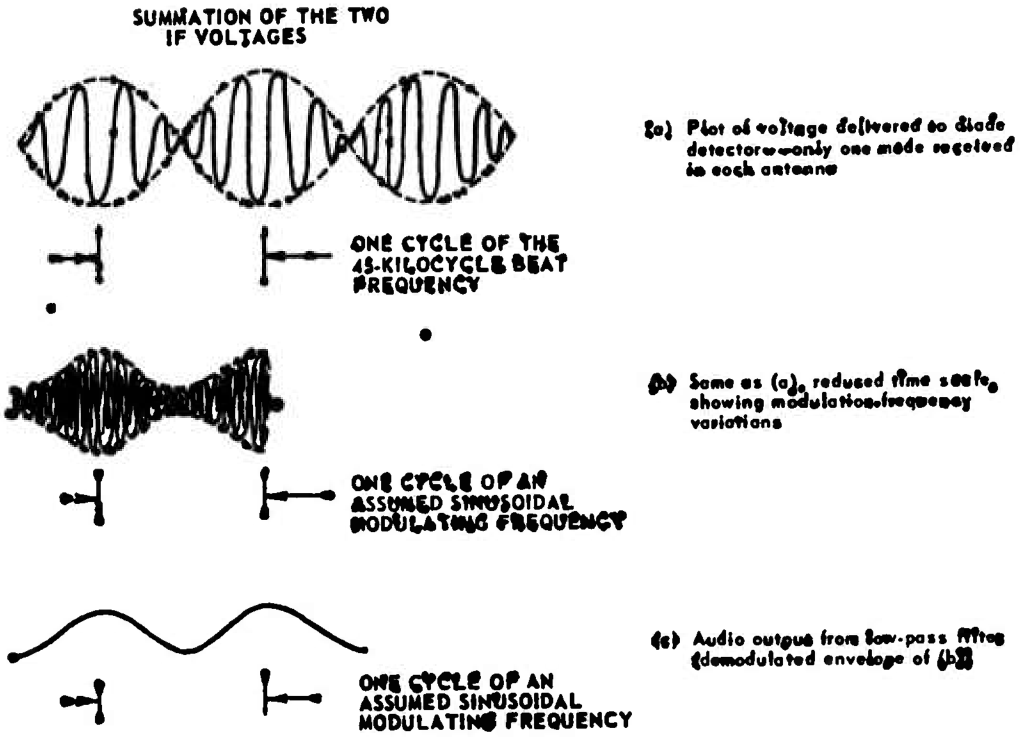


FIG. 4. DIODE DETECTOR WAVEFORMS, AS IN FIG. 3, FOR CASE WHERE ONLY ONE INCOMING MODE IS PRESENT, AS IN FIG. 1(a)

When more than one incoming mode is present, the action of the combiner can be visualized with the aid of Fig. 5. Assume for simplicity that only two modes are present, as in Fig. 1(c), and that they are of equal intensity. Assume that the two receivers of Fig. 3, connected to their respective antennas, are producing the idealized polar-pattern variation illustrated in Fig. 2(c), and that this variation repeats once per cycle of 45-kc difference frequency. The resultant i-f voltage which is applied to the diode detector can be found by constructing phasor diagrams such as those shown in parts (d), (e), and (f) of Fig. 2. The variation of the amplitude of this resultant during one cycle of the 45-kc difference frequency is shown at the left in Fig. 5. Parts (a), (b), and (c) of Fig. 5 illustrate the envelope of this resultant for the three conditions of relative phase between the two mode voltages. On the right-hand side in Fig. 5 are shown amplitude-vs-frequency curves for a single

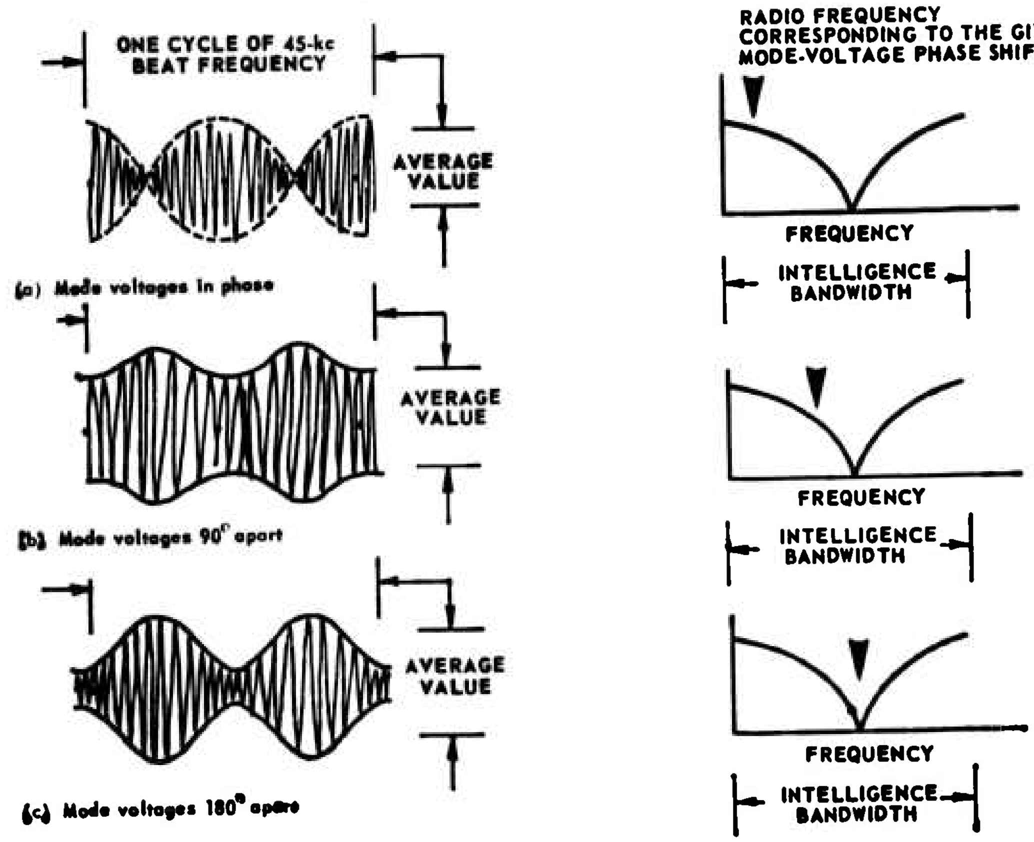


FIG. 5. DIODE DETECTOR INPUT-VOLTAGE WAVEFORMS WHEN TWO MODES PRESENT, FOR DIFFERENT RELATIVE MODE VOLTAGE PHASES, SHOWING EQUIVALENT RADIO FREQUENCY.

antenna and receiver, with arrows indicating the points in the radio-frequency spectrum corresponding to the three assumed relative mode-voltage phases.

In Fig. 5(a), the two mode voltages are assumed to be in phase. When that condition applies, a simple receiver would find a maximum in the frequency spectrum at the operating frequency. For the phase-shifter setting which results in the polar pattern shown in the middle diagram of Fig. 2(c), the two mode voltages will be received with equal amplitude. One will be received in one lobe of the antenna, and the other in the other. Since the phase of voltage picked up in one lobe will be reversed with respect to that picked up in the other, at that particular instant in the phase shifter or difference-frequency cycle, the two mode voltages cancel and the resultant is zero. However, for the other two polar patterns corresponding to the other positions of the phase shifter

illustrated in Fig. 2(b), the mode-voltage resultant is not zero. Thus, if an average of the resultant voltage is taken over one cycle of the difference frequency (i.e., over one sweep of the antenna polar pattern) a finite output is obtained. The value of this average, for all three relative mode-voltage phases, is indicated in the center of the figure.

Note that when the relative mode phase is 180 deg, which results in a null at the operating frequency in the simple receiver, the mode-averaging receiver has an output whose average over one cycle of pattern variation is also finite.

Similarly, a quadrature phase relationship between the mode voltages results in an average value not far different from the averages for the other two values of relative mode phases.

The voltage appearing at the output terminals of the low-pass filter of Fig. 3 is the running average (over the 45-kc difference frequency) of the sum of the two i-f voltages fed to the diode detector. The variation of this average with relative phase of the individual mode voltages is shown in Fig. 6. Since the different relative phases correspond to

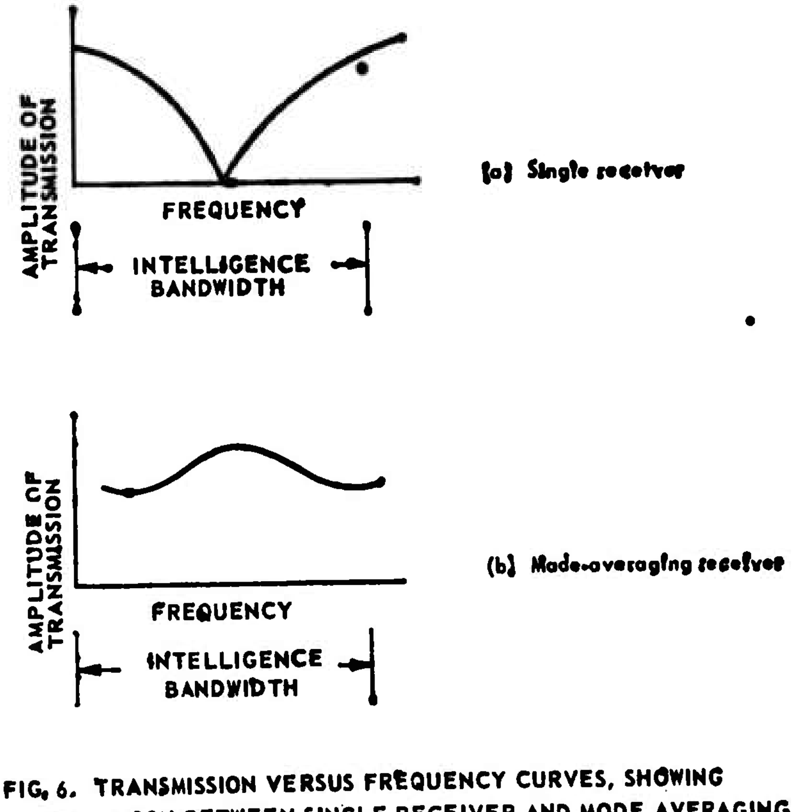


FIG. 6. TRANSMISSION VERSUS FREQUENCY CURVES, SHOWING COMPARISON BETWEEN SINGLE RECEIVER AND MODE-AVERAGING RECEIVER, WHEN TWO EQUAL MODES ARE PRESENT.

different radio frequencies, Fig. 6 is also a plot of amplitude of response vs radio frequency, which may be compared directly with that of the simple receiver. In the mode-averaging receiver, the frequency distortion over the intelligence bandwidth is considerably reduced, although some is still present. To the extent that frequency distortion is reduced, modulation should sound more natural. In addition, with amplitude modulation, the intervals of overmodulation distortion due to weakness of the carrier should be less frequent and less intense.

IV. ADDITIONAL COMMENTS

The idealized polar patterns of Fig. 2(b) will not be too well approximated by the simple interferometer arrangement illustrated in part (a) of that figure. However, it can be appreciated that virtually any kind of a polar-pattern variation resulting from an effective phase shift between the two pickup antennas will tend to reduce the depth of a null in the transmission band of a simple antenna and receiver. An optimum arrangement would very probably call for a very deep null which is swept through the entire range of downcoming wave angles constituting a given received signal. However, it seems clear that less-than-ideal polar-pattern changes will still give useful advantage.

A practical difficulty will be that of keeping the relative gains of the two receivers nearly equal over the complete AGC characteristic, since any departure from gain equality at some particular value of AGC voltage will have the effect of reducing the depth of the desired null. It can also be seen that there is no simple way to check this gain equality by inspection of the i-f waveform across the input to the diode detector. Since more than two incoming modes will be present during much of the time in practice, it can be appreciated that the i-f waveforms of Fig. 5 may be very complex.

Spacing the antennas transversely with respect to the direction of the distant radio transmitter will produce much less effective mode averaging, since signals tend to arrive along the great circle. Antennas transversely spaced produce one or more pattern nulls which sweep in azimuth, rather than elevation. To a first approximation, a multipath-interference-caused null in the received transmission band will not be altered by variation of the azimuthal polar pattern of the receiving antenna. However, in practice azimuthal polar-pattern variation is seldom accomplished without some incidental vertical-plane-pattern variation, which would undoubtedly contribute some useful mode averaging.

In addition, in the case of very long radio-transmission paths, the arriving signal energy (although roughly centered on the great circle) often deviates momentarily quite substantially from the great-circle direction. It is entirely possible that the amplitude-of-transmission-vs-frequency characteristic of signals deviated out of the great circle may

differ substantially from that of energy which happens to have traveled within the great-circle plane. To the extent that this is true, useful mode averaging might be accomplished by changes in azimuthal polar pattern only.

V. APPLICATION TO SINGLE-SIDEBAND RECEPTION

In order for this technique to function properly in the case of single-sideband transmission, the reduced or missing carrier must be resupplied or exalted within each receiver prior to the diversity-combining operation itself. This is necessary for the proper operation of the diode detector. In the case of reduced-carrier reception, only one carrier-selecting and exalting circuit would be required, since by use of common local oscillators (except for the last intermediate-frequency conversion), drift in the receivers can be cancelled.

VI. COMPARISON WITH OTHER COMBINERS

The dual, space-diversity, amplitude-modulation, radiotelephone combining technique of Ref. 1 calls for two receivers so interconnected that the common audio output at any instant is supplied entirely by that receiver whose antenna picks up the strongest carrier component. Since reception in this situation is effectively that of one receiver and one antenna, mode-interference-caused frequency distortion will inevitably be present. The principal advantage afforded by this arrangement is reduction of overmodulation distortion caused by fading of the carrier. The same advantage may also be had--at lower cost--by use of exalted-carrier reception.

Frequency distortion cannot be eliminated by simple addition of two independently received and independently fading sets of sidebands. Even though a "hole" in one sideband spectrum will appear to be filled by a maximum in the other, "holes" at other positions in the combined spectrum will be created by interference between oppositely phased signal components. Double-sideband amplitude modulation is in reality dual frequency-diversity, single-sideband transmission with linear addition of the audio voltages derived from each set of side frequencies. It is well known that no fading advantage results from this arrangement.

A recent approach to dual space-diversity combining in single-sideband radiotelephone practice calls for division of the audio-frequency range into three equal subbands, which might be designated as A, B, and C. The total speech energy in subband A obtained from one antenna is compared with the total energy in subband A derived from the second antenna. By means of an audio mixer whose setting varies in accordance with the square of the ratio of the two subband signal strengths, the common output (in the frequency range of audio subband A) is in effect supplied from that antenna receiving the strongest signal in subband A. Thus, if mode interference causes a null to appear in the subband A range of one antenna, the missing audio frequencies can in general be supplied by the subband A output of the other antenna.

The principal difficulties with this approach are practical. The subband-selecting filters tend to introduce phase distortion at the

edges of their passbands, which may result in irregularities in the overall transmission-vs-frequency characteristic. Careful initial relative-gain settings are required for best performance of the ratio-squared combiners, calling for skill and attention on the part of operators. Finally, it is found in practice that these adjustments, once found, tend to drift with time, thus requiring continued supervision on the part of operating staff.

The reason for this drift is subtle, and appears to be the following. With few exceptions, receiving stations are built on sites having local terrain irregularities. Thus, there will be minor, but nonetheless significant, differences in the vertical polar patterns of identically constructed, spaced antennas. Ionospheric transmission normally involves a multiplicity of hops; thus, received signal energy will arrive at a variety of vertical angles. Furthermore, the relative intensity of each of these signal components will change slowly with time, owing to polarization changes and to the variable focusing effect of ionospheric inhomogeneities. These changes typically have periods in the order of minutes. It can accordingly be expected that the total sideband energy picked up in two antennas having slightly differing vertical polar patterns will slowly drift with time, as the intensities of signal components at the various vertical angles change. It is this drift that tends to upset the optimum setting of relative gain in the two pairs of audio-frequency channels.

In mode-averaging combining, the two antennas of a space-diversity pair are in effect electrically interconnected and form two elements of what can then be considered to be single interferometer antenna, or array. In the other methods of combining, the two antennas are in reality used one at a time, except for comparatively brief transition intervals.

VII. AN ALTERNATIVE MODE-AVERAGING COMBINER ARRANGEMENT

The essence of the mode-averaging-combiner approach is the concept of a continuous variation of the relative amplitudes of the various mode components with respect to one another, over the range of possibilities, so that an average of the resultant (over one cycle of the variation) can be found. In this way, it is never possible for the mode components completely to cancel one another out, at some given radio frequency, thereby producing a transmission null at that frequency. The transmission null will always be broken up by altering the relative magnitudes of the mode components, so that an average over one cycle of the (pattern) variation will have a finite value.

The same effect cannot be achieved by simple switching between the outputs of the two receivers, as might at first seem plausible.

A mode-averaging-combiner arrangement alternative to that shown in Fig. 3 takes advantage of the fact that the polarization of the various received mode components differs, in general, from one to another. Thus, the relative intensities of the various mode voltages can be changed merely by rotating the plane of polarization of the receiving antenna. If the antenna is a simple dipole (or the equivalent), this rotation can be synthesized electronically, at a high rate of speed. The probability that the received signal, at any given radio frequency, will disappear completely during an entire rotation of the antenna, is comparatively small.

Figure 7 shows how this might be done. In this situation the receivers are identical, with identical i-f output frequencies. Conversion oscillators must be locked together in phase. The receiver outputs are connected to a balanced-modulator-like arrangement, which varies the relative magnitudes and phases of the receiver outputs in such a way that there is delivered to the diode detector a voltage equivalent to that from a simple receiver connected to a physically rotated dipole.

Once again, the low-pass filter averages over the effective antenna rotation period and permits the audio intelligence to be passed.

It is possible, of course, for this combiner to be deceived by certain special situations. For example, suppose that only two incoming

modes were present at some radio frequency, that their instantaneous phases were in exact opposition, and that their polarization was exactly the same. In that event, antenna rotation would be of no avail. However, the probability that both signal components should have exactly equal polarizations at any given instant seems small.

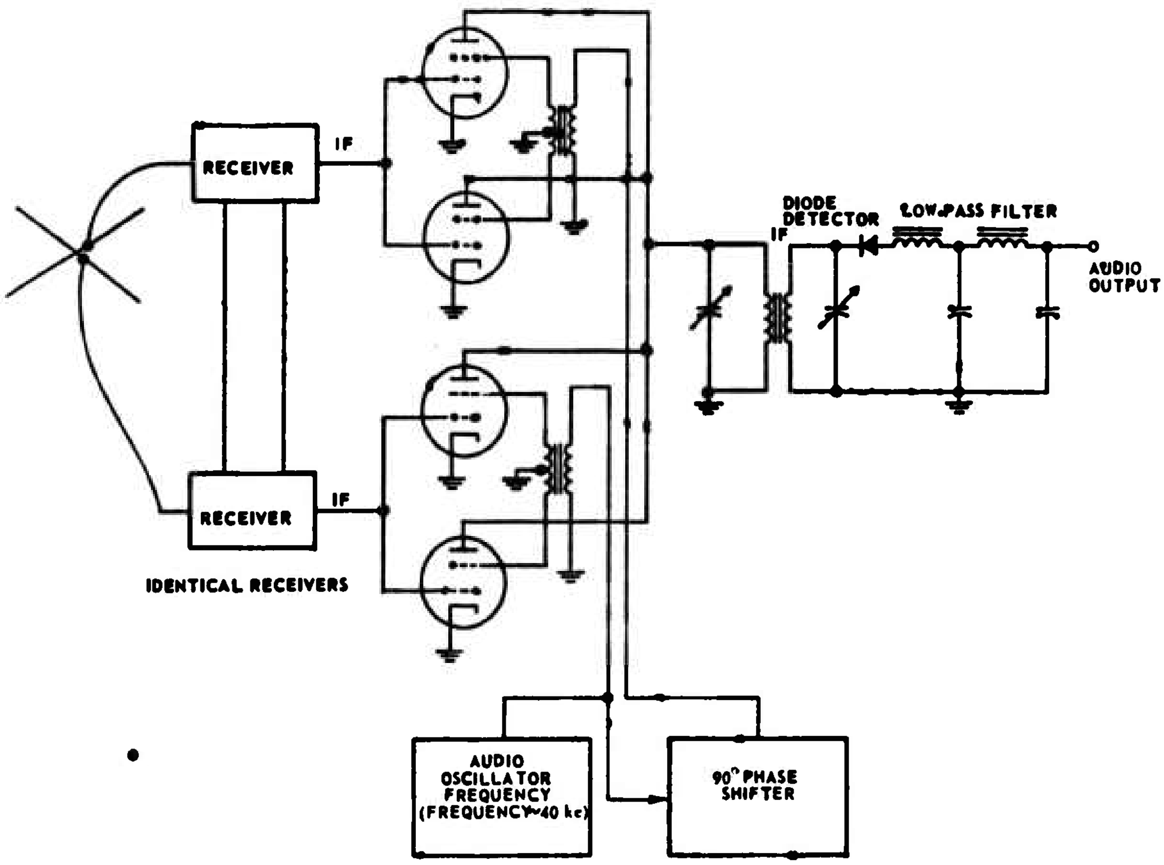


FIG. 7. SIMPLIFIED, ROTATING-POLARIZATION DIVERSITY COMBINER.

VIII. CONCLUSIONS

Mode-averaging diversity combining of either kind does not require any more antennas or receivers than are now used in dual space-diversity receiving installations. They therefore appear to be practicable alternatives to existing schemes.

It can be said that, whereas existing combiners accept the mode interference and attempt to patch up the trouble after it has happened, the mode-averaging combiner attacks the trouble at its source, by breaking up the conditions which permit establishment of a mode-interference transmission null in the modulation passband.

When compared with simple combining of the conventional kind, mode-averaging combining appears to offer significantly better performance. When compared with the more sophisticated versions of conventional radiotelephone diversity combining, mode averaging appears to offer greater operating simplicity.

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